University of Central Florida

CREOL
The College of Optics and Photonics

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Defense Technical Information Center
8725 John J Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

Subject: Grant N00014-14-1-0447

On behalf of Dr. Konstantin Vodopyanov, we are pleased to submit the attached Interim Report due December 31, 2015 for the above referenced grant titled "Novel concept of frequency-combs interferometric spectroscopy in the mid-ir for significantly enhanced detection of explosives".

For technical questions, please contact Dr. Vodopyanov at vodopyanov@creol.ucf.edu or 407-823-6818. All other administrative or contractual questions should be directed to Arlisia Potter, Sr. Contract Manager, at apotter@ucf.edu.

Sincerely,

Vicky Ortiz

Vicky Ortiz, M.A.
Coordinator of Research Programs
UCF College of Optics and Photonics, CREOL & FPCE
Phone: 407-823-6825, Fax: 407-823-6880
vsortiz@creol.ucf.edu

CC: Naval Research Laboratory, ATTN Code 5596, 4555 Overlook Avenue, SW, Washington, DC 20375-5320

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14. ABSTRACT
Our work over the reporting period has resulted in the demonstration of high performance spectroscopic sensor based on mid-IR frequency combs. Ultrasensitive detection of methane, isotopic carbon dioxide, carbon monoxide, formaldehyde, acetylene, and ethylene was performed in the spectral range 2.5–5 μm using intracavity spectroscopy in broadband optical parametric oscillators (OPOs). The OPOs were operated near degeneracy and synchronously pumped either by a mode-locked erbium (1560 nm) or thulium (2050 nm) fiber laser. A large instantaneous bandwidth of up to 1000 cm−1 allows for detection of several substances simultaneously.

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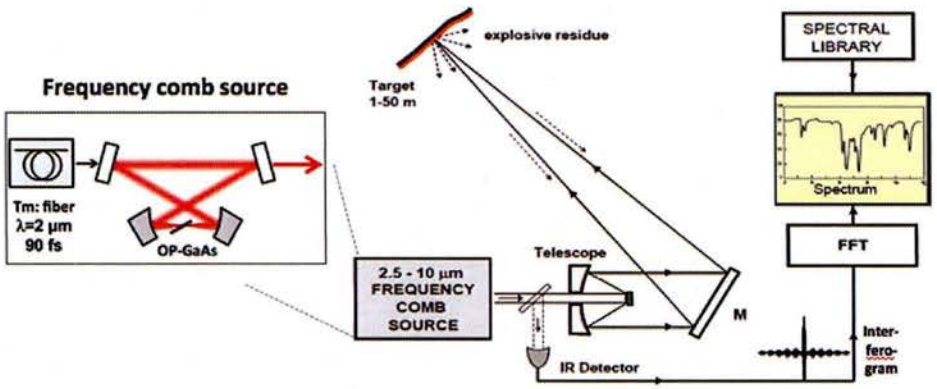
Progress report, December 2015

ONR grant: N00014-10-1-0281, "Novel concept of frequency-combs interferometric spectroscopy in the mid-IR for significantly enhanced detection of explosives"

1. **Prime Offeror:** Robert L. Byer, Stanford University
2. **Subcontractor:** Konstantin L. Vodopyanov, CREOL, Univ. Central Florida
3. **Period of Performance:** June 2013 - Dec 2015 (after no cost extension)
4. **Business Contact:** Dr. Konstantin Vodopyanov, CREOL, College of Optics and Photonics, Univ. Central Florida, Orlando, FL 32816, tel. (407) 823 6818, vodopyanov@creol.ucf.edu

Our work over the reporting period has resulted in the demonstration of high performance spectroscopic sensor based on mid-IR frequency combs. Ultrasensitive detection of methane, isotopic carbon dioxide, carbon monoxide, formaldehyde, acetylene, and ethylene was performed in the spectral range 2.5–5 μm using intracavity spectroscopy in broadband optical parametric oscillators (OPOs). The OPOs were operated near degeneracy and synchronously pumped either by a mode-locked erbium (1560 nm) or thulium (2050 nm) fiber laser. A large instantaneous bandwidth of up to 1000 cm^{-1} allows for detection of several substances simultaneously. We observed an effective path-length enhancement due to coherent interaction inside the OPO cavity and achieve part-per-billion sensitivity levels. This sensor can be used for remote and in-situ sensing of TNT, RDX, PETN and other explosives.



Standoff trace detector based on mid-infrared frequency comb. The mid-infrared 'signature' spectrum is obtained from the time-domain interferogram from a photodetector.

Main accomplishments:

1) Achieved frequency comb from an OPO based on PPLN crystal with a wavelength span of 2.5 – 3.9 μm

□

2) Achieved frequency comb from an OPO based on OP-GaAs crystal with a wavelength span of 2.6 – 6.1 μm (more than an octave, world record)

□

3) Demonstrated trace point detection of methane, carbon dioxide, isotopic (13CO2) carbon dioxide, carbon monoxide, ethylene, acetylene, and formaldehyde and achieved part-per-billion sensitivity levels.

□

4) Demonstrated a new technique for extending octave-wide frequency combs to the highly desirable yet difficult-to-achieve mid-IR fingerprint spectral range.

□

5) Our new technology of broadband mid-IR combs may have a major impact on trace explosive and chem/bio hazard detection, in terms of sensitivity, selectivity and speed

□

Presentations and publications related to the Grant

1) Publications:

1. M. W. Haakestad, A. Marandi, N. Leindecker, and K. L. Vodopyanov, "Five-cycle pulses near $\lambda = 3$ μm produced in a subharmonic optical parametric oscillator via fine dispersion management", Laser & Photonics Rev. 7, L93–L97 (2013)

2. J. Kiessling, I. Breunig, P. G. Schunemann, K. Buse and K. L. Vodopyanov,"High power and spectral purity continuous-wave photonic THz source tunable from 1 to 4.5 THz for nonlinear molecular spectroscopy", New Journal of Physics 15, 105014 (2013)

3. Charles W. Rudy, Alireza Marandi, Konstantin L. Vodopyanov, and Robert L. Byer, "Octave-spanning supercontinuum generation in in situ tapered As2S3 fiber pumped by a thulium-doped fiber laser", Opt. Lett. 38, 2865-68 (2013)

4. Charles W. Rudy, Alireza Marandi, Konstantin L. Vodopyanov, Robert L. Byer, "In-situ tapering of chalcogenide fiber for mid-infrared supercontinuum generation", J. Vis. Exp. (JoVE) 75, e50518 (2013)

5. K. F. Lee, J. Jiang, C. Mohr, J. Bethge, M. E. Fermann, N. Leindecker, K. L. Vodopyanov, P. G. Schunemann, and I. Hartl, "Carrier envelope offset frequency of a

doubly resonant, nondegenerate, mid-infrared GaAs optical parametric oscillator," Opt. Lett. 38, 1191-1193 (2013)

6. M. K. Trubetskov, M. von Pechmann, I. B. Angelov, K. L. Vodopyanov, F. Krausz, and V. Pervak, "Measurements of the group delay and the group delay dispersion with resonance scanning interferometer," Opt. Express 21, 6658-6669 (2013)

7. M. W. Haakestad, T. P. Lamour, N. Leindecker, A. Marandi, and K. L. Vodopyanov, "Intracavity trace molecular detection with a broadband mid-IR frequency comb source", J. Opt. Soc. Amer. B 30, 631-640 (2013)

8. C. W. Rudy, A. Marandi, K. A. Ingold, S. J. Wolf, K. L. Vodopyanov, R. L. Byer, L. Yang, P. Wan, and J. Liu, "Sub-50 fs pulses around 2070 nm from a synchronously-pumped, degenerate OPO", Opt. Express 20, 27589-27595 (2012)

9. M. Vainio, M. Merimaa, L. Halonen, and K. Vodopyanov, "Degenerate 1 GHz repetition rate femtosecond optical parametric oscillator", Opt. Lett. 37, 4561-4563 (2012)

10. A. Marandi, C. W. Rudy, V. G. Plotnichenko, E. M. Dianov, K. L. Vodopyanov, R. L. Byer, "Mid-infrared supercontinuum generation in tapered chalcogenide fiber for producing octave-spanning frequency comb around 3 μm", Opt. Express 20, 24218-24225 (2012)

11. A. Marandi, N. Leindecker, K. L. Vodopyanov, R.L. Byer, "All-optical quantum random bit generation from intrinsically binary phase of parametric oscillators", Opt. Express 20, 19322-19330 (2012)

12. A. Marandi, N. Leindecker, V. Pervak, R.L. Byer, K. L. Vodopyanov, "Coherence properties of a broadband femtosecond mid-IR optical parametric oscillator operating at degeneracy", Opt. Express 20, 7255-7262 (2012)

13. N. Leindecker, A. Marandi, R.L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann "Octave-spanning ultrafast OPO with 2.6-6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser", Opt. Express 20, 7047-7053 (2012)

2) Invited Presentations:

"Producing Octave-Wide Combs And Few-Cycle Pulses In The Mid-Infrared: Frequency Divide-And-Conquer Approach" Frontiers in Optics/Laser Science 2013, Orlando, Florida, 6-10 Oct. 2013

"Producing octave-wide combs and few-cycle pulses in the mid-IR: frequency divide-and-conquer approach" The 10th Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2013), Kyoto, Japan, 30 June- 4 July 2013

"Cascaded generation of octave-spanning 2–5 μm frequency combs via subharmonic-supercontinuum process", A. Marandi, C. W. Rudy, K. L. Vodopyanov, R. L. Byer Photonics West, San Francisco, Feb. 2013

"Frequency divide-and-conquer approach to producing octave-wide combs and few-cycle pulses in the mid-IR" Konstantin Vodopyanov, Ultrafast Optics Conference (UFO), Davos, Switzerland, March 2013

"Producing octave-wide combs and few-cycle pulses in the mid-infrared: frequency divide and-conquer approach" Konstantin Vodopyanov, The US-UK Workshop in Mid-IR to THz Technology and Applications, Edinburgh, UK, 18 Feb. 2013

"Resonantly-enhanced photonic generation of monochromatic 0.5-5 THz radiation using periodically-inverted GaAs" Vodopyanov, Konstantin L. Terahertz Workshop, March 25-27, 2013 Cargèse, Corsica, France

"CW Tm:fiber lasers for THz generation" International Symposium on Photoelectronic Detection and Imaging (ISPDI), 25-27 June 2013, Beijing, China

"High power and spectral purity continuous-wave photonic THz source tunable from 1 to 4.5 THz for nonlinear molecular spectroscopy" International Symposium on Photoelectronic Detection and Imaging (ISPDI), 25-27 June 2013, Beijing, China

"Frequency divide-and-conquer approach to producing octave-wide mid-infrared frequency combs" Konstantin Vodopyanov, Laser Optics, St-Petersburg, Russia, 26 June 2012

"Mid-IR frequency combs - enabling technology for noninvasive medical testing" Konstantin Vodopyanov, JSAP-OSA meeting, Matsuyama, Japan, Sept. 2012

"Mid-IR frequency combs based on subharmonic OPO: frequency-divide-and-conquer approach " Konstantin Vodopyanov CLEO, San Jose, May 2012

"Producing octave-wide frequency combs in the mid-IR: frequency-divide-and-conquer approach " Konstantin Vodopyanov, The International Symposium on Photonics and Optoelectronics (SOPO 2012), Shanghai, China, 22 May 2012